Novel Acoustic Techniques for Assessing Fish Schooling in the Context of an Operational Ocean Observatory

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LONG-TERM GOALS

The goal of this work is to develop new methods for observing large spatial scales in oceanic ecosystems. In particular, this report focuses on the development and use of a new type of mid-frequency, multi-beam sonar for making long-range backscatter images of fish aggregations in shallow water with the aid of the ocean acoustic waveguide. Fish aggregation is important during spawning, predation, and feeding, yet the quantitative analyses of gregarious movements and behaviors remain relatively rare. Measurements of fish aggregations are often difficult, particularly in pelagic environments. In terms of the forward sonar problem, widespread fish aggregations will appear as interfering reverberation, while schools and shoals may appear as false targets or may screen other targets, degrading sonar system performance.

OBJECTIVES

Observations of large spatial scales in oceanic ecosystems can be made using low- to mid-frequency sonar with the aid of the ocean waveguide to extend the range of backscatter imagery. Such observations use sonar images in horizontal coordinates, in contrast to the more conventional use of high-frequency down-looking sonars for echo integration. Synoptic two-dimensional horizontal images of the ocean can be created by beamforming a towed or fixed horizontal array, as opposed to piecing together vertical profiles of the water column obtained from a moving platform. While high-frequency side-looking sonars have been used to a limited degree for biomass estimates at short horizontal ranges [Smith:1970, Thomas:1987, Thorne:1998, Pedersen:1999], lower frequencies offer the potential of longer range imaging owing to lower attenuation and reduction of spreading loss in the waveguide sound channel. A recent example of this approach is the use of a 400 Hz towed array to observe the formation processes of large fish shoals at ranges up 15 km during spawning [Makris:2009, Makris:2006].

The objective of this project is to develop and deploy a new type of mid-frequency multi-beam sonar that is capable of imaging fish at long ranges in shallow water environments, exploiting the affects of waveguide propagation, while being physically smaller and easier to deploy than existing towed array systems. Conceptually, the system is designed to observe spatial scales on the order of several meters at ranges up to several kilometers, depending on the water depth. This scale is smaller than images created with large towed line-array systems, but larger than the horizontal scales possible with traditional fisheries echo-sounder systems. The system is also capable for deployment in a fixed location (unlike moving ship systems), enabling observations of fish aggregation behavior as a function of time from a single location. This is useful for observing a broad range of temporal scales.

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14. ABSTRACT
The goal of this work is to develop new methods for observing large spatial scales in oceanic ecosystems. In particular, this report focuses on the development and use of a new type of mid-frequency, multi-beam sonar for making long-range backscatter images of fish aggregations in shallow water with the aid of the ocean acoustic waveguide. Fish aggregation is important during spawning, predation, and feeding, yet the quantitative analyses of gregarious movements and behaviors remain relatively rare. Measurements of fish aggregations are often difficult, particularly in pelagic environments. In terms of the forward sonar problem, widespread fish aggregations will appear as interfering reverberation, while schools and shoals may appear as false targets or may screen other targets, degrading sonar system performance.

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While images may offer immediate insight into fish behavior, they should also provide quantitative biomass information, given a means of compensating for the effects of propagation. As range increases, waveguide boundary reverberation and propagation effects accumulate and can bias the quantitative analysis of imagery. Inverting waveguide backscatter for estimates of fish density, for example, requires a model of the multipath structure and the resultant transmission loss and pulse spreading. So in addition to developing new sonar hardware and imaging methods, numerical models have been developed to simulate waveguide backscatter. The inherent complexity of waveguide propagation, the complex spatial and temporal behavior of fish, combined with the difficulty of making ground-truth measurements over large areas of the ocean, necessitate the use of models to interpret field data.

An important objective of the field component this project was to correlate the results of the longer-range measurement (less understood and more complex scattering geometries) with more traditional higher-frequency, split-beam fisheries echo-sounding techniques and direct sampling. A portion of the field sampling was conducted within the New Jersey Shelf Observing System (NJ SOS), which provides real-time data throughout the Mid-Atlantic Bight (MAB). In all of the field experiments, down-looking sonar surveys were used to identify and track schools of fish associated with hydrographic and biological structure. This approach was deigned to provide a context for the long-range imagery, and combined with other oceanographic measurements and expertise, allowing us to begin to look for correlations between the fish biology and environmental variability.

APPROACH

Mid-frequency sonar development

There are no commercial sonar systems capable of imaging large horizontal areas of the ocean using the waveguide, other than Navy towed line-array systems. Ship mounted swath bathymetry systems, side-scan sonars, and split- or single-beam echosounding systems generally do not have sufficient horizontal array aperature for waveguide imaging. Horizontal aperature provides the necessary array gain and beamforming resolution to form images with sufficient SNR and spatial resolution to resolve weak signals form fish schools at longe range. These limitations are evident in previous attempts [Smith:1970, Thomas:1987, Thorne:1998, Pedersen:1999], as compared with recent applications using a Navy towed array [Makris:2009, Makris:2006].

The approach taken in this project was to develop a prototype, horizontally oriented, multi-beam sonar with sufficient beamforming resolution and flexibility in processing to investigate new methods of waveguide imaging. Figure 1 illustrates the system being deployed. The operating frequency of 12 kHz was chosen to maximize sonar range in a waveguide, while minimizing array size (approximately 4' diameter, 5' height). The array is circular, enabling a circular horizontal images of the ocean to be formed with a single transmission. Towed arrays and sidescan systems requires forward motion and ship maneuvers to image a desired section of the ocean. The circular array can be fixed in space while forming an instantaneous, two-dimensional, horizontal images of a circular region of the ocean. In this capacity, the array is well suited for long-term observation, such as in the context of a cabled obsevatory or moored system. Because the array is relatively smaller, it can be deployed over the side of a stationary ship, much like a CTD rosette. In this capacity, the system can rapidly image an area of the ocean in responce to traditional down-looking acoustic surveys and/or other remote platforms (i.e. AUVs and gliders) and oceanographic measurements.

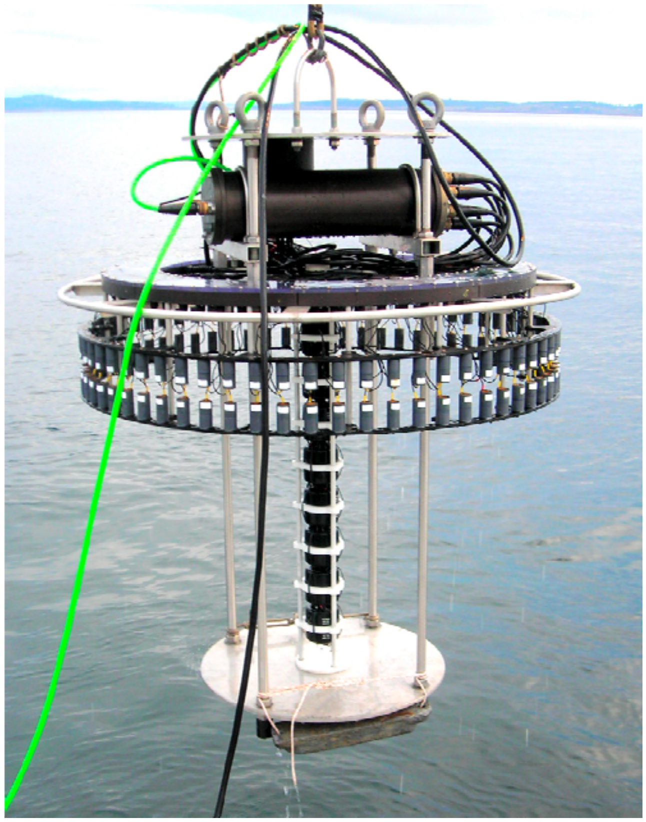

Figure 1. Pelagic Imaging Mid-frequency Sonar (PIMS)

The PIMS (Pelagic Imaging Mid-frequency Sonar) system shown in Figure 1 consists of a circular receiving array and a linear transmitting array. The circular receiving array has multiple receiving hydrophones (64) that form steered receiving beams with ~5 degrees of horizontal resolution. The transmit array has 16 elements, creating a projected beam that is narrow ~9 degrees in the vertical dimension and omni-directional (360 degrees) in the horizontal direction. The imaging resolution of the system is defined by the intersection of the receiver and transmitter beams (~ 5x9 degrees beams).

Figure 2 illustrates the imaging geometry and two deployment configurations. A circular, horizontal image is created by transmitting a pulse and recording backscatter as a function of time/range along multiple radials in the waveguide. Multiple transmissions in time form a time series of backscatter images. Multiple rapid images in time at a fixed location can improve image quality by averaging incoherent noise, while enhancing weak coherent signals. Multiple images over longer time periods can be used to observe fish behavior and horizontal spatial structure.

Field Experiments

Field deployments were prmarily designed to test the long range imaging capabilities of the new sonar system. Various deployment and imaging configurations where performed including deployment over the side of a drifting and anchored ship, and 24 hour deployments with an anchored buoy/battery system. In each deployment, ship surveys using a down-looking sonar (EK60) were used to ground truth fish distributions. Direct sampling with fish trawls were used when available. CTD casts were used to obtain profiles for characterizing the sound waveguide.

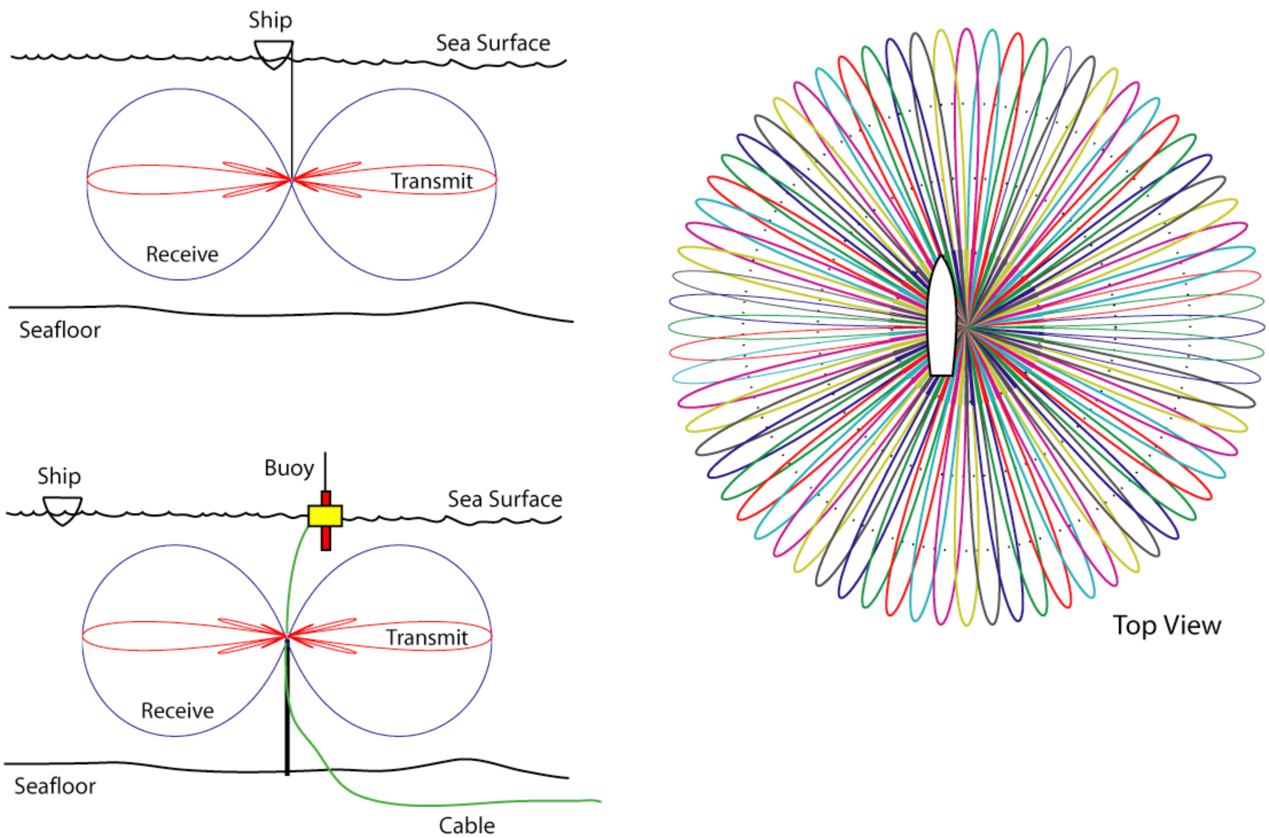

Figure 2: PIMS imaging geometry and deployment configurations illustrating horizontal imaging from a ship and mooring. The sonar simultaneously images a circular area of the ocean with electronically form beams that are approximately 5 degrees horizontal and 9 degrees vertical.

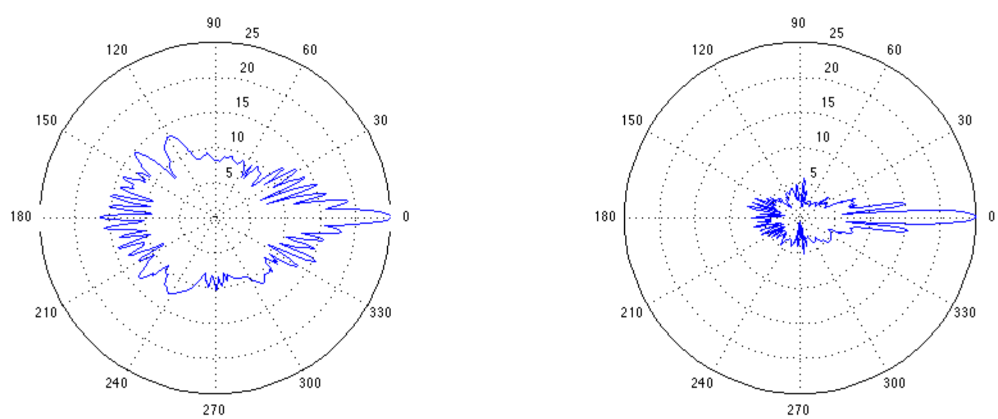

Figure 3: Two type of beamforming developed for the PIMS array. The left figure shows a fast beamforming method developed of near real-time imaging that has less resolution and higher side and back lobes. The right figure shows an improved beamforming method that can be used in postprocessing to improve image quality.

RESULTS

Mid-frequency sonar development

APL-UW has completed the design, fabrication, and testing of the Pelagic Imaging Mid-frequency Sonar (PIMS). Initial system testing/calibration was conducted at the APL test facilty. Prior to at-sea deployments, a significant effort was devoted to developing the beamforming and imaging capabilities for the new system. Imaging fish at long range requires extracting weak signals from noisy data and devising new strategies for collecting and processing data, significantly different than traditional multibeam data processing. Figure 3 illustrates two different approaches to beamforming, showing beam patterns derived from the same calibration data. The less accurate and faster method of phase-shift beamforming (shown in the left panel) is used to form images rapidly in near real-time. The better time-delay method (shown in the right panel) is used in postprocessing to extract weak signals. The right panel also illustrates a typical beam pattern realized with the new circular array, showing very good back and side lobe supression. Note that there is no left/right amiguity with a circular array, as there is with towed line arrays.

Field Experiments

The sonar was successfully deployed in four geographicaly discinct areas with many hours of sampling. The first deployment was aboard the NOAA R/V Freeman at Kodiak Island in 2006. The goal for the first field season was primarily testing, although pollock aggrgations were detected and sampled. Subsequent field tests focused on the development of sampling and processing techniques (e.g. different ways to deploy the array, how to integrate the sonar in surveys, improved signal processing). Two field deployments were performed off the New Jersey coast and in the Chesapeake Bay as part of joint experiment on the R/V Sharp in 2006 and 2007. The final experiments were in the Puget Sound in 2008 using the R/V Robertson.

A large amount of data was collected in a variety of configurations. Data processing is preliminary and on-going. Examples of data from two locations are summarized below, illustrating two different spatial scales of waveguide imagery. The first example (Figure 4) shows images of small fish schools in very shallow water (10 m) at ranges on the order of 100 meters. The second example shows an image of a larger school in typical continental shelf water depth (100 m) at longer range of the order 1 km.

No large and persistent fish schools were detected during the first three field experiments, either by the PIMS system or by EK60 surveys. Shoals of small fish (likely smelt) were imaged in the last field experiment in the Puget Sound. Work is on-going in terms of this objective, but initial data results are compelling.

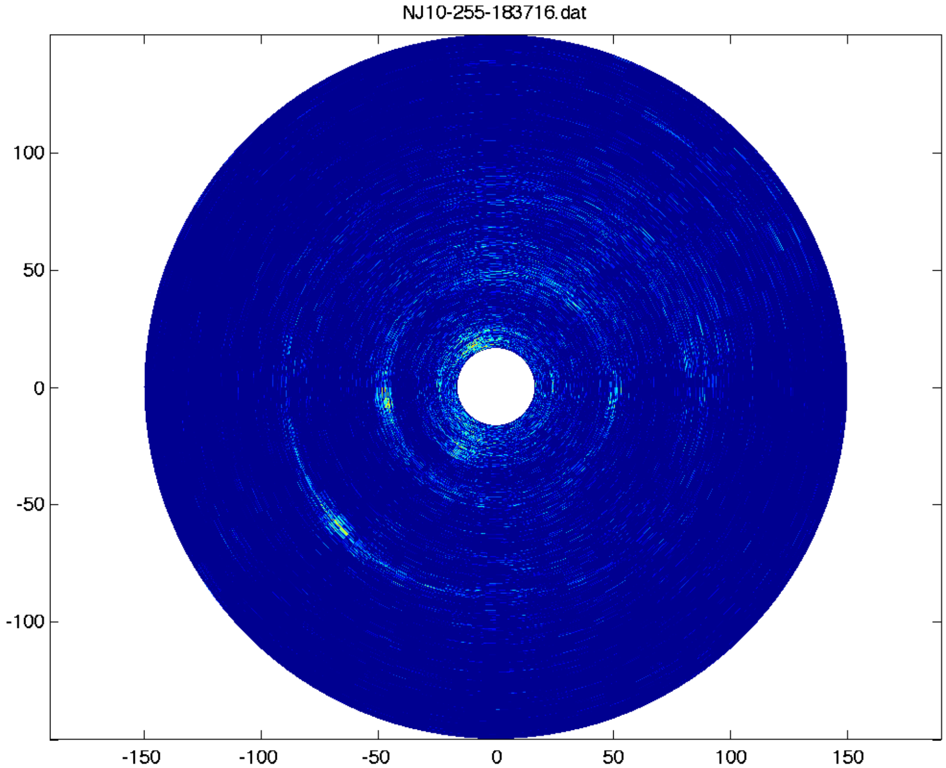

Figure 4. Image of aggregations of bay anchovies in the Chesapeake Bay. Several aggregations are show in the backscatter image at ranges up to 100 meters from the PIMS array. The water depth was 10-20 meters. The color scale is in units of dB

Chesapeake Bay: Preliminary analysis of the PIMS acoustic data recorded in the Chesapeake Bay show imaging of bay anchovy aggregations (Figure 4) corresponding to observations made with downward looking multibeam sonar and groundtruthing using a variey of trawls. Figure 4 illustrates one example of a circular horizontal image with several aggregations. Each aggregation in the image is approximately 5 to 10 meters in diameter. In this example aggregations were imaged a range of 100 meters in water depths of approximately 10-20 meters, illustrating nicely the waveguide scattering geometry in very shallow water.

Puget Sound: Data collected during NOPP field experiments in the Puget Sound of Washington State better illustrate the PIMS system data in more typical shallow water environments. Figure 3 illustrates a 1 km circular image of area near Middle Bank in the Puget Sound, WA. In the area of the image, shoaling fish would rise during the night from daytime bottom layers. During the day, the near-bottom layers were not visible in the images or were indistinguishable from background reverberation. At night, identifiable areas of increased backscatter were observed and associated with aggregations of fish rising to mid-water, as observed separately with a down-looking EK60. These fish shoals (believed to be smelt) are relatively weak targets, comparable in level to scattering and reverberation associated with topography. The strong scattering at the upper right of the image is backscatter from the rising slope of Middle Bank.

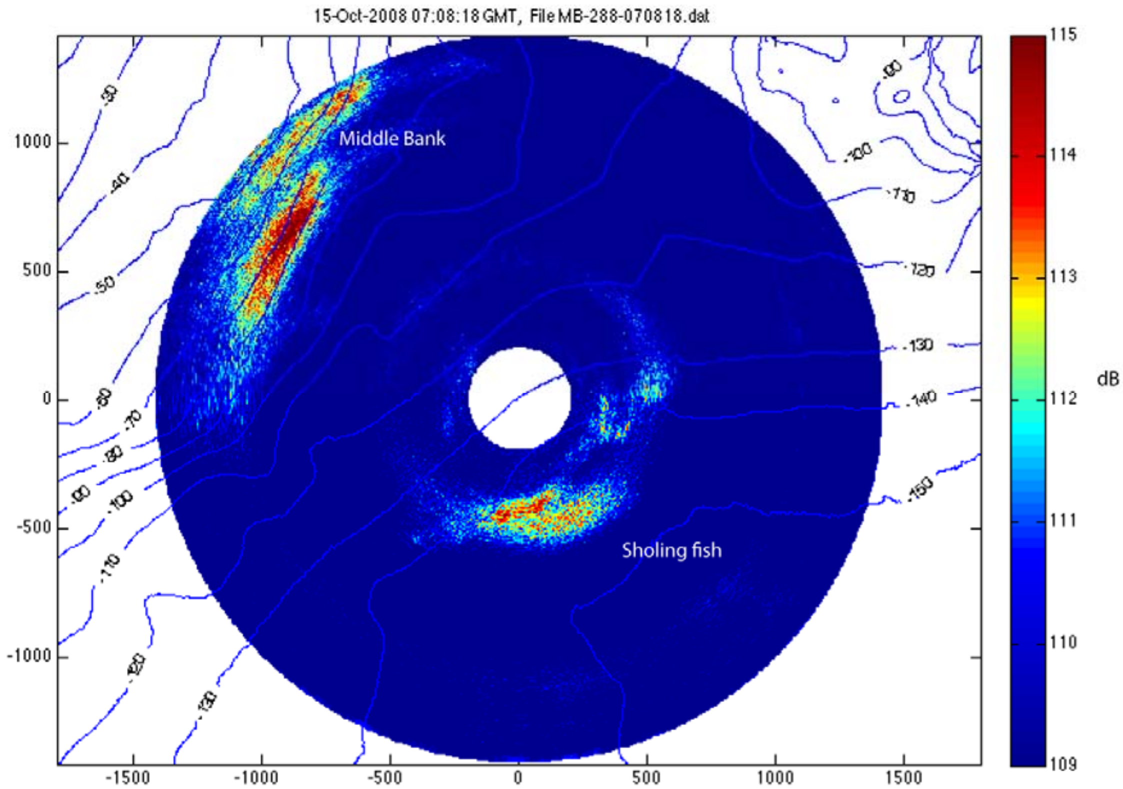

Figure 5. Shoaling fish in the Puget Sound imaged with the 12kHz PIMS sonar. The circle marks an area of fish emerging from the bottom just after dawn, as observed with an EK60. The blue lines are 10 meter bathymetric contours.

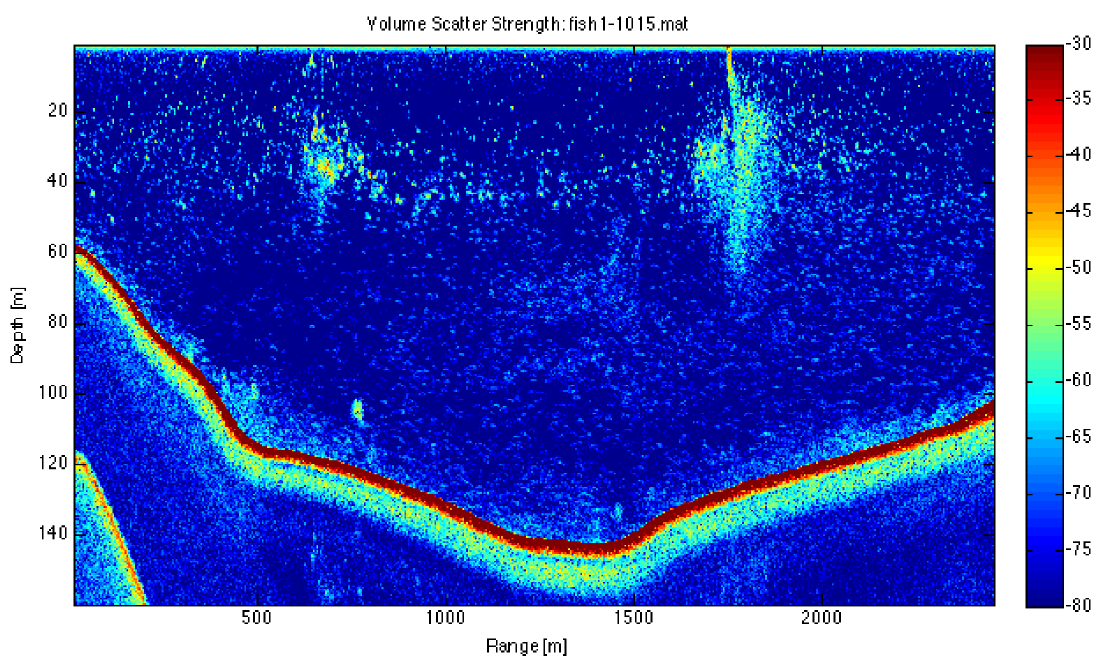

Figure 6. EK60 backscatter (down looking) from fish shoals imaged in Fig.5.

Numerical Modeling

A model of scattering from fish combined with range and depth dependent waveguide propagation is a necessary first step for interpreting field data. Towards this objective, a model has been developed and tested to numerically simulate scattering from random schools of fish sing waveguide geomtries similar to data collected in the field experiments. To simulate scattering from fish only, the waveguide is modeled with a flat sea surface, a homogeneous flat bottom, and linear sound speed profiles. Future simulations will combine random scattering from fish with random media scattering in realistic oceanic waveguides with rough interfaces and inhomogeneous media. But this is not done in the current effort.

A complete description of the model is being published [Jones:2009b]. However, the procedure for estimating backscatter from fish aggregations involves numerical PE propagation simulations combined with simulations of scattering from fish. The MMPE model [Smith:2001, Smith:2008] is used to model propagation in this effort. However, any standard PE model could be used. Parameters defining the waveguide are taken from the ONR Special Workshop on Shallow Water Reverberation ftp://ftp.ccs.nrl.navy.mil/pub/ram/RevModWkshp_II, date last viewed 8/15/09.

Backscatter from an aggregation of fish is found using a single scatter model and numerically generated PE envelope functions. Time-domain simulations of backscatter are formulated numerically using Fourier synthesis and broadband PE solutions. Monte-Carlo simulations with multiple realizations of random fish populations are used to estimate statistics of the backscattered field. Individual fish are modeled as point scatterers with an isotropic scattering strength. The isotropic scattering amplitude for each fish is modeled using a resonant bubble model [Love:1978, Love:2003]. More complex scattering functions for individual fish can be modeled by representing a single fish as a collection of point scatterers [Huang:1980]. Fish schools are modeled as a cluster of point scatterers with random locations taken from the spatial probability density function defined by Problem F of the Workshop on Shallow Water Reverberation. Total mean backscattered intensity is found as the average of the squared baseband signal magnitude over the finite number of realizations.

Several simulation examples are given here to illustrate some of the more important effects the waveguide has on scattering from fish. Figures 7, 8, and 9 show mean backscatter intensity as a function of range along a single radial passing through the center of the fish school. Simulation of multiple radials using directional source and receiver beam patterns would be used to form a two-dimensional waveguide image.

Figure 5 shows the mean backscatter intensity for a school as function of range. In this figure the fish are centered at mid water depth (50 m) at ranges 1 km, 5 km and 10 km. The equivalent fish bubble radius of a = 0.008 m is used, which is resonant at 1 kHz and 50 m depth. As a result, the scattering amplitude is a strong function of depth with a maximum at 50 m. Cylindrical spreading loss has been removed from the simulated data by multiplying the backscattered pressure by a factor equal to the horizontal range in meters. Hence, the vertical axis is taken as dB Pa @ 1 m.

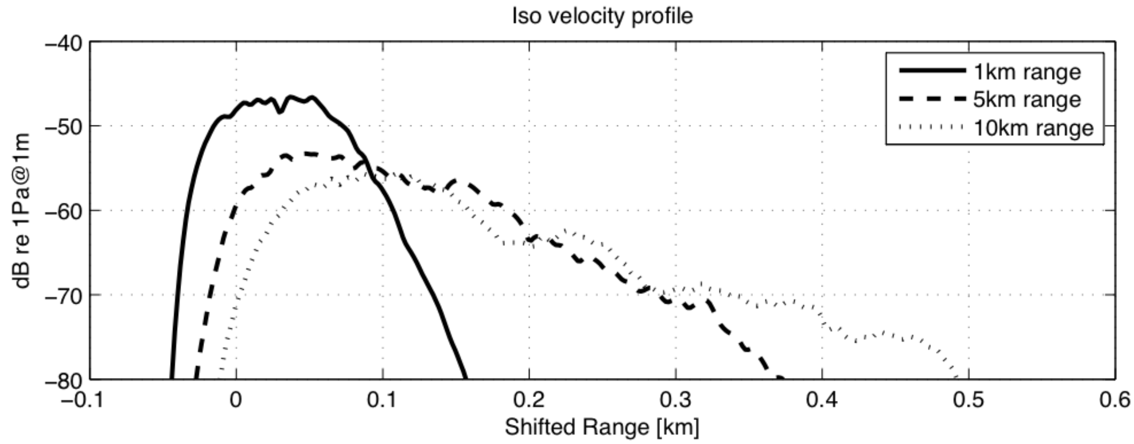

Figure 7. Mean backscatter intensity of mid-water fish school in a waveguide as a function of range with an iso-velocity profile. Cylindrical spreading has been removed. The range has been shifted by subtracting the horizontal distance to the school center.

A simple cylindrical-spreading model would predict that all three echos have the same magnitude in Fig. 7, and this is definitely not the case. Thus, use of a heuristic cylindrical spreading loss model for this waveguide would lead to a large errors when estimating fish density by echo integration methods. Estimates for the boundaries of the school would also be distorted by multi-path spreading of the incident and scattered pulse.

Figure 8 compares the intensity of backscatter from a fish school at different depths and for two different sound speed profiles. Here the fish school is centered at a range of 5 km, but the depth takes on values 10 m, 50 m, and 90 m. The sound speed profile in the upper panel is downward-refracting, referred to as a winter profile. The lower panel shows backscatter from the same fish school with an iso-velocity profile. The bubble radius is a = 0.02 m, which at 1 kHz gives a scattering strength that is approximately constant as a function of depth to avoid confusing depth-dependent scattering strength with propagation effects. Changes in propagation due to the sound speed profile significantly affect the backscatter. In this case, the winter profile shows a strong depth dependence in backscatter, as opposed to the iso-velocity profile, for the same fish schools.

Figure 9 shows the mean and variance of backscatter intensity for a school centered at 1 km, a center depth of 50 m, and equivalent bubble radius is a = 0.008 m. Scattering from a single realization of a fish school (solid line) is compared to the mean backscattered intensity (dashed line) and variance (dotted line) of 100 realizations. The envelope of the mean intensity is an indicator of the shape of the fish school, with the trailing edge of the signal elongated due to multipath in the waveguide. Since scattering from many fish leads to Gaussian fluctuations in the complex backscattered pressure (Rayleigh envelope statistics), large fluctuations can be expected in a backscatter image without sufficient ensemble averaging. Averaging to reduce statistical fluctuations in field measurements of backscatter, for example, can be achieved by averaging multiple pings over time, assuming the positions of the individual fish have changed between pings and that the overall shape and size of the fish school remains the same.

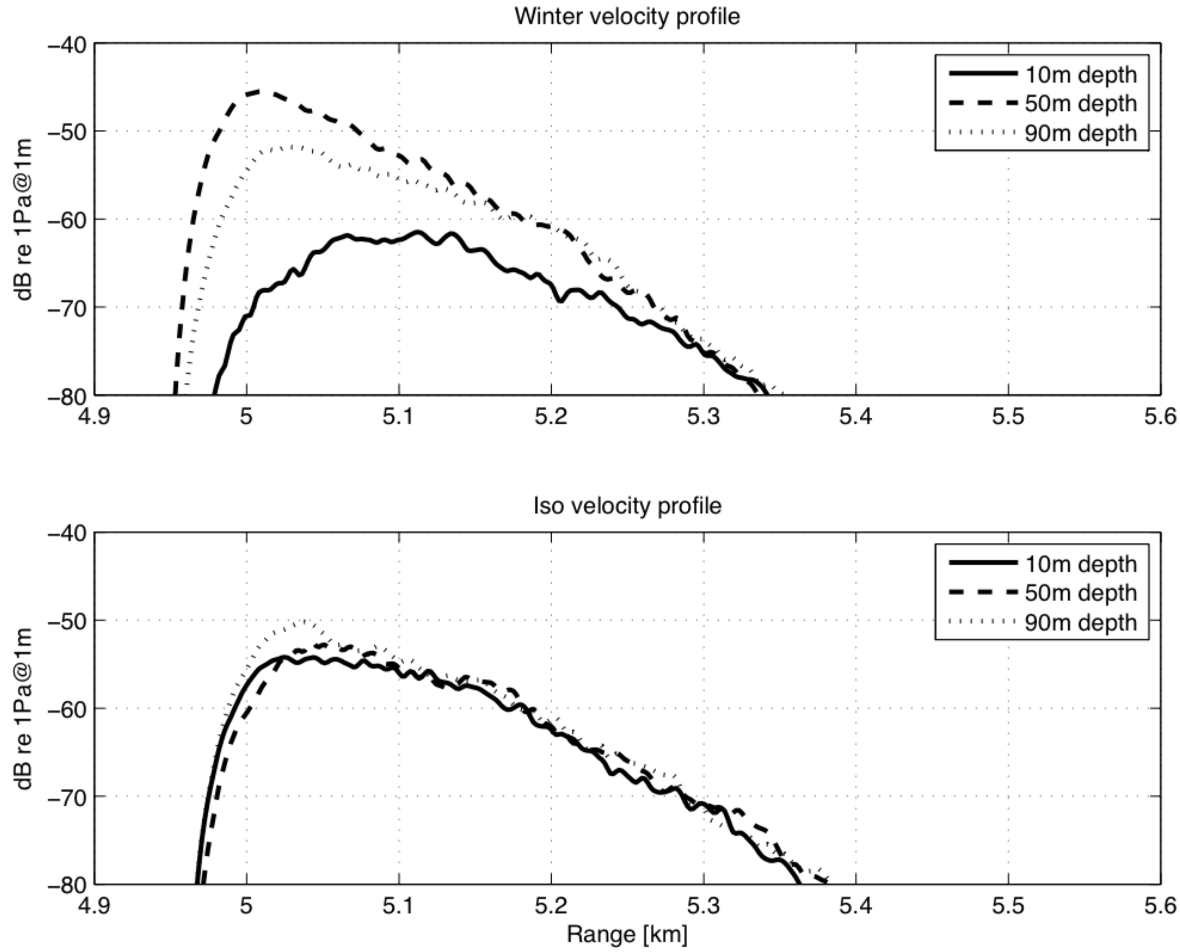

Figure 8. Mean backscatter intensity of a fish school in a waveguide as a function of school depth = 10, 50, 90 meters for two velocity profiles: downward refractive, winter profile (upper panel); and iso-velocity profile (lower panel). Cylindrical spreading has been removed. The horizontal distance to the school center is 5 km.

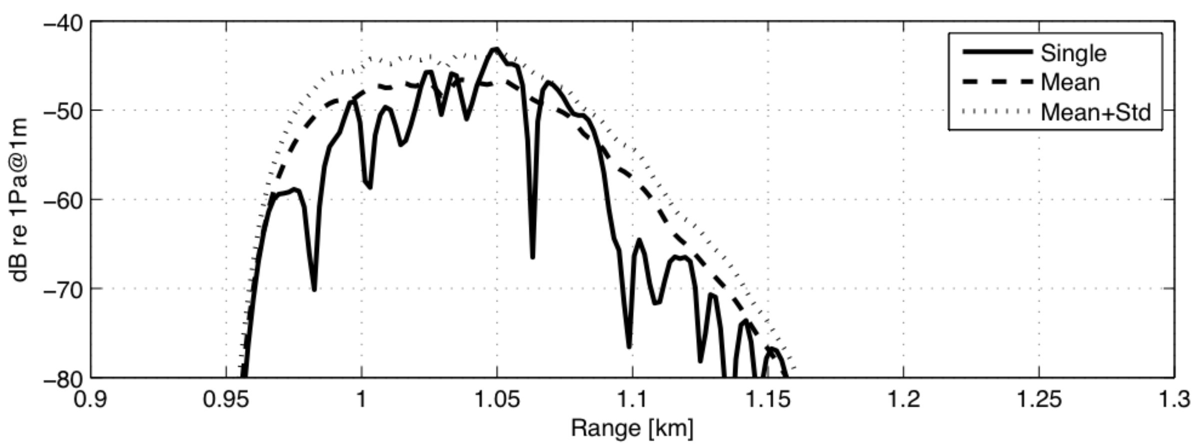

Figure 9. Variability of backscatter from a mid-water school of fish in a waveguide showing the simulated back scatter intensity from a single realization, the mean intensity for 100 realizations, and the upper standard deviation of 100 realizations. Cylindrical spreading has been removed. The horizontal distance to the school center is 1 km.

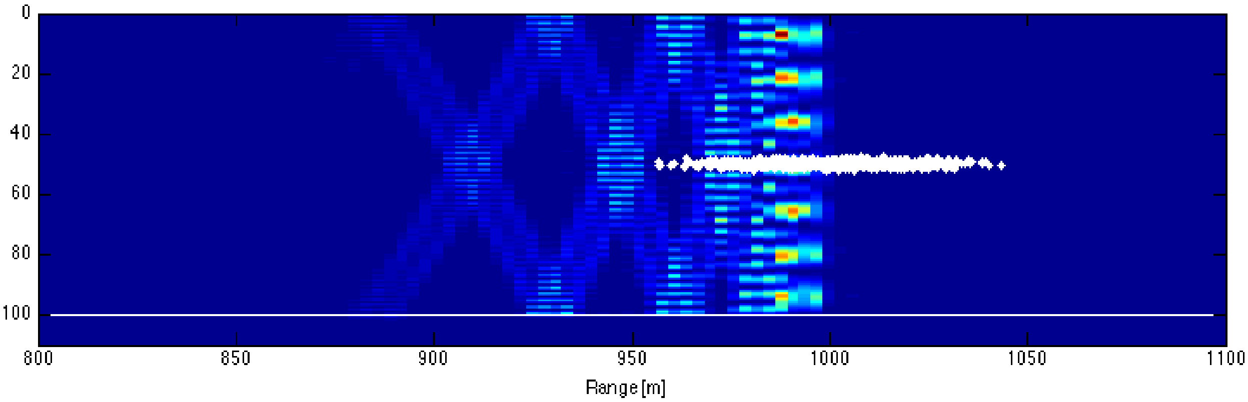

Figure 10. Pulse propagation in a waveguide with an iso-velocity profile. The fish school is 100m wide and 5m thick and centered at 1km range from the source. The intensity of the pulse is plotted with red as high and blue as low.

Further insight is gained by illustrating a snapshot in time of a 1kHz pulse that has traveled 1000 meters in a shallow iso-velocity waveguide (Figure 10). The image in Figure 10 is a vertical slice of the waveguide with depth on the ordinate (z-axis) and range on the abscissa (x-axis). A simulated fish school is located at mid-water depth. Strong horizontal and vertical multi-path structure in the waveguide is evident, resulting in the type of depth dependence of scattering as shown in Figure 8.

All of these issues (propagation loss, pulse spreading, sound speed profile, variability, etc.) complicate the image interpretation and analysis. Figure 11 illustrates the formation of a fish school backscatter image (looking down from above). Here an image is formed using multiple, steered beams to sample the horizontal extent of a fish school, whereas Figures 7 through 9 are single radials. Backscatter along each radial in azimuth (or steered beam) is plotted as pixels on the horizontal coordinates of the waveguide (x, y). In this image the azimuthal beam width of 2 degrees was used. A single realization of scattering is plotted in Figure 11 with the fish school centered at (x, y, z)=(1000,0,50) in meters. The positions of the fish are drawn as white points. The image on the left is backscatter from a fish school at 50 meters depth, and the image on the right is backscatter from the same school at 10 meters depth. When the fish are near the surface there is a greater than 10 dB decrease in the backscatter intensity. In addition to the level of scattering, the random fluctuations and elongation of the backscattered signal envelope make it difficult to identify the boundaries of the fish school (shown in the figures as white dots).

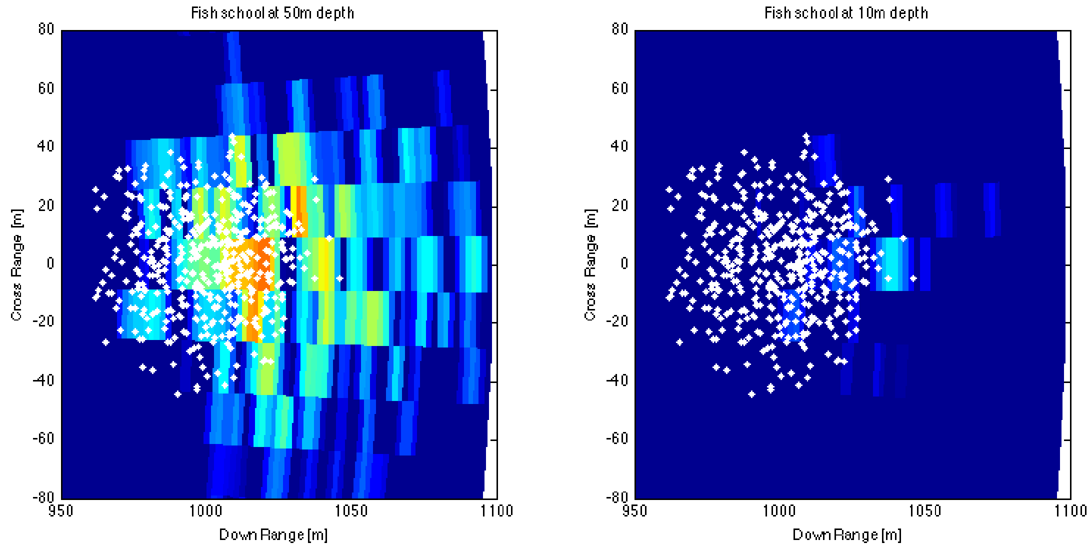

Figure 11. Simulated backscatter imaging of a fish school in a waveguide with the fish at different depths. The left image is the school at 50m in depth. The right image is the same school at a depth of 10m. Backscatter intensity is plotted with a decibel color scale ranging from -60 dB (red) to -85 dB (blue). Cross-range resolution is found by beamforming with 2 degree horizontal beams. The down range resolution is defined by the pulse length.

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